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The ATLAS High-Level Calorimeter Trigger in Run-2

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Abstract.

The ATLAS Experiment uses a two-level triggering system to identify and record proton-proton collision events containing a wide variety of physics signatures. It reduces the event rate from the bunch crossing rate of 40 MHz to an average recording rate of 1 kHz, whilst maintaining high efficiency for interesting collision events. It is composed of an initial hardware-based level-1 trigger followed by a software-based high-level trigger. A central component of the high-level trigger is the calorimeter trigger. This is responsible for processing data from the electromagnetic and hadronic calorimeters in order to identify electrons, photons, taus, jets and missing transverse energy. This paper presents the performance of the high-level calorimeter trigger in Run-2, noting the improvements that have been made in response to the challenges of operating at high luminosity.

1. Introduction

The ATLAS Trigger [1] is the system responsible for the online selection of proton-proton collision events to be recorded for physics analyses. The experimental conditions in Run-2 of the Large Hadron Collider (LHC) [2] have posed a number of challenges to the operation of the ATLAS Trigger. The centre-of-mass energy and the instantaneous luminosity have both increased with respect to Run-1. The cost of this has been an increase in the mean number of proton-proton interactions per bunch crossing (μ), which in turn leads to an increase in background activity in the detector - an effect known as *pile-up*. The μ -values observed in Run-2 are shown in Figure 1. The increase in pile-up can result in an increase in trigger rates. The ATLAS Trigger has therefore taken various measures to ensure that trigger rates are kept at acceptable levels in Run-2, whilst maintaining sensitivity to the physics program of the ATLAS Experiment [3].

2. The ATLAS Trigger

The ATLAS Trigger consists of a hardware-based Level-1 (L1) Trigger and a software-based High-Level Trigger (HLT). The L1 Trigger reduces the event rate from the bunch crossing rate of 40 MHz to 100 kHz. The events are selected based on reduced granularity data from the calorimeter and muon spectrometer, with limited energy resolution. The L1 Trigger also identifies *Regions of Interest* (RoIs) in the $\eta - \phi$ plane to seed event processing at the HLT, where the event rate is reduced from 100 kHz to the data recording rate of ~ 1 kHz. The full event information is available at the HLT and events are selected using reconstruction algorithms that



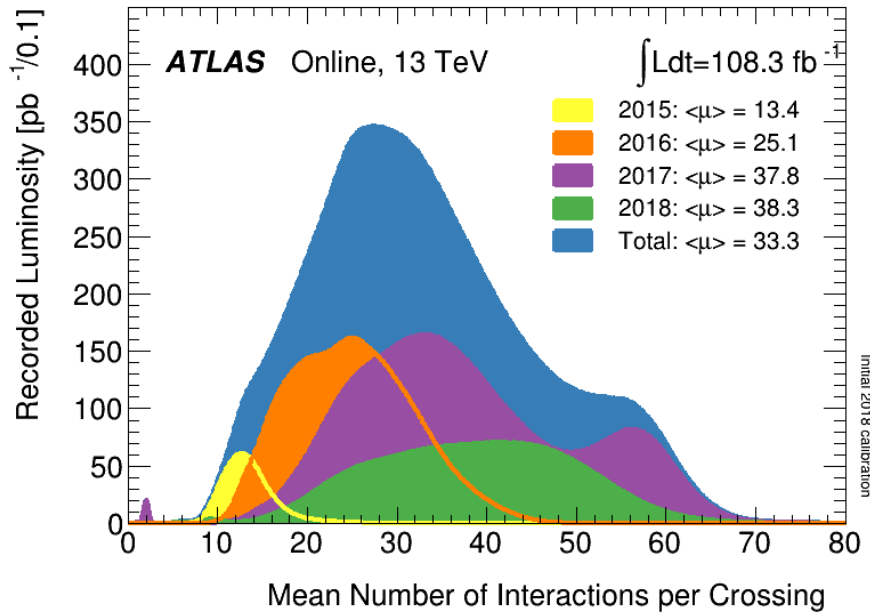


Figure 1. The luminosity-weighted distributions of μ for the different periods of data-taking in Run-2 [4].

are as similar as possible to those used in the offline reconstruction. The algorithms run on a CPU farm of $\sim 50,000$ CPUs and can process data either from within the RoIs identified at L1 or from the full detector. A schematic overview of the ATLAS Trigger and Data Acquisition system in Run-2 is shown in Figure 2. More information on the ATLAS Trigger in Run-2 can be found in [1].

3. The High-Level Calorimeter Trigger

The High-Level Calorimeter Trigger refers to the software responsible for converting raw data from the calorimeter into objects, specifically *cells* and *clusters*, which then serve as input to the reconstruction of electron, photon, tau and jet candidates and missing transverse energy (E_T^{miss}). These cells and clusters are also used in determining the shapes of particle showers and the isolation properties of candidate particles (including muons), both of which are later used as discriminants for particle identification and the rejection of background. The cell-building algorithm first retrieves the raw data from the calorimeter. This can be done in one of two ways: either by retrieving the data from within the RoIs (*RoI-based* mode) or by retrieving the data from the full calorimeter (*full-scan* mode). The RoI-based mode is used for localized objects, i.e. electrons, photons and taus, whereas the full-scan mode is used for jets and global event quantities such as E_T^{miss} . In both cases the raw data is converted into a collection of cells. Two different clustering algorithms are then used to reconstruct clusters from the collections of cells: the *sliding-window* algorithm [6] and the *topo-clustering* algorithm [7]. The sliding window algorithm is used for the reconstruction of electron and photon candidates whereas the topo-clustering algorithm is used for the reconstruction of tau and jet candidates and E_T^{miss} .

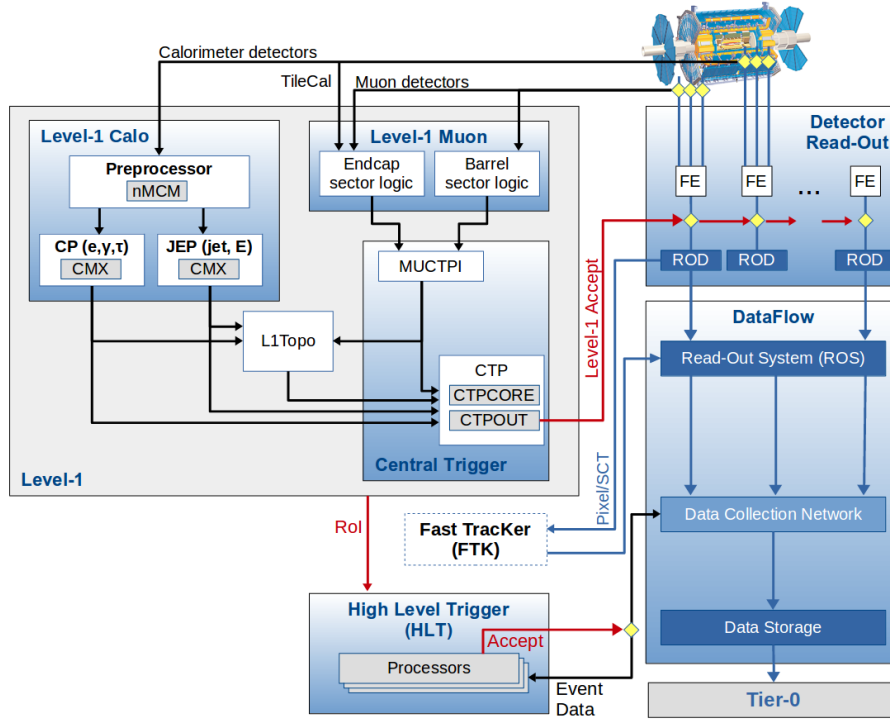


Figure 2. A schematic diagram of the ATLAS Trigger and Data Acquisition (DAQ) system in Run-2 [5].

3.1. Algorithm Timing

After Run-1 there was a significant effort to reduce the execution time of the cell-building and topo-clustering algorithms. This allowed for the cell-building and the subsequent topo-clustering to be performed in full-scan mode as the first step in the HLT for jet and E_T^{miss} triggers - thus improving the harmonization between the online and offline reconstruction. For the cell-building algorithm, the DAQ readout system was improved and a specially optimized infrastructure with a memory caching mechanism was implemented, allowing for very fast retrieval of the raw data - even from the full calorimeter, which comprises more than 187,000 cells. For the topo-clustering algorithm a number of optimizations were made, which included improving memory management and avoiding calls to CPU-intensive functions wherever possible. As an example of the latter, the addition of a new cell to a cluster had triggered a recalculation of the clusters energy and position. This calculation is now only performed once, after we know the full set of cells associated to the cluster. The mean execution time for the algorithms operating in full-scan mode in Run-2 are: 20 ms for the cell-building and 82 ms for the topo-clustering. These represent a reduction in the mean execution time with respect to Run-1 by a factor of 5 and 3, respectively. The execution times for the topo-clustering algorithm operating in full-scan mode in Run-2 are shown in Figure 3.

3.2. Out-of-Time Pile-up Effects

In 2016 cell-level energy corrections to account for *out-of-time* pile-up were introduced at the HLT. Out-of-time pile-up refers to the influence of proton-proton interactions in previous bunch crossings, which is possible due to the fact that the lengths of the bipolar pulse shapes in the

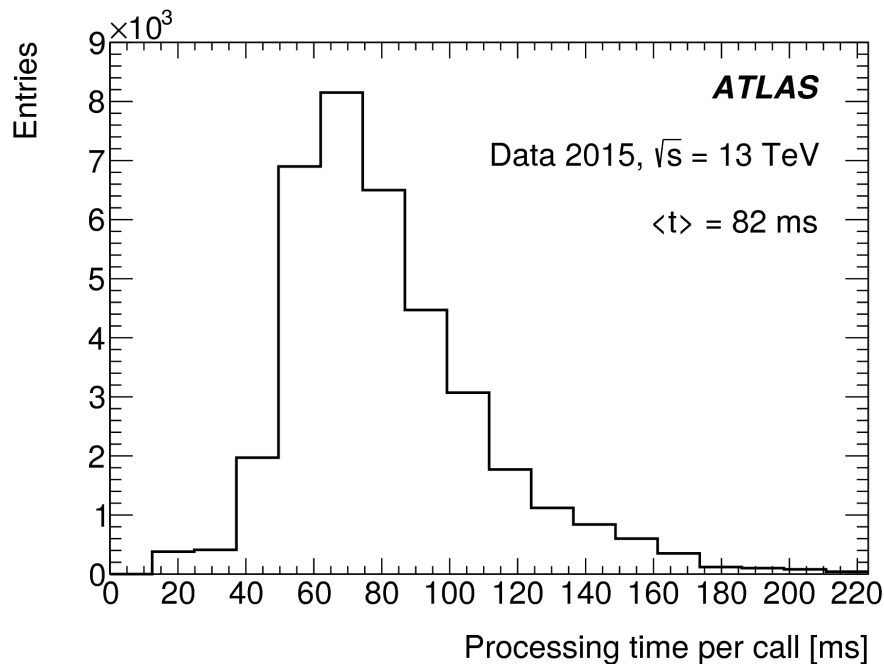


Figure 3. The distribution of execution times for the topo-clustering algorithm operating in full-scan mode in Run-2 [1].

Liquid Argon (LAr) calorimeter ($\mathcal{O} \sim 400$ ns) are much greater than the 25 ns bunch spacing. It can lead to so-called *bunch train effects*, in which the events at the beginning of each bunch train exhibit a positive shift in energies due to the fact that these bunch crossings only experience the positive (and not the negative) components of the bipolar pulse shapes. The effect can be seen in Figure 4 and can result in increased trigger rates at the beginning of each bunch train. The energy corrections were incorporated into the cell-building and are similar to those that are being applied in the offline reconstruction. They are applied to all LAr cells on an event-by-event basis (at a cost of ~ 1 ms per event) and represent the estimated average shift in energy for each cell. The calculations of these shifts in energy requires an estimate of the luminosity per event. The HLT has only periodic access to luminosity information and, as such, the luminosity per event can only be known to within $\sim 5\%$ of the luminosity used in the offline reconstruction. This results in some residual differences between the online and offline performance of the energy corrections.

3.3. Performance in Run-2

The improved harmonization between the online and offline reconstruction in Run-2 means that the online performance is now much closer to the offline performance. At the beginning of Run-2 the HLT showed good performance in terms of the E_T resolution of the HLT clusters with respect to their offline counterparts: the E_T resolution of the sliding window clusters was 3% for clusters above 5 GeV, while the E_T resolution of the topo-clusters was 2% for clusters above 10 GeV [1]. For 2015 both the sliding-window clusters and the topo-clusters at the HLT exhibited a slight positive shift in their energies, with respect to offline energies. This was found to be due to out-of-time pile-up effects and was resolved by the introduction of the cell-level energy corrections at the HLT in 2016, which improved the energy resolution for all calorimeter-based

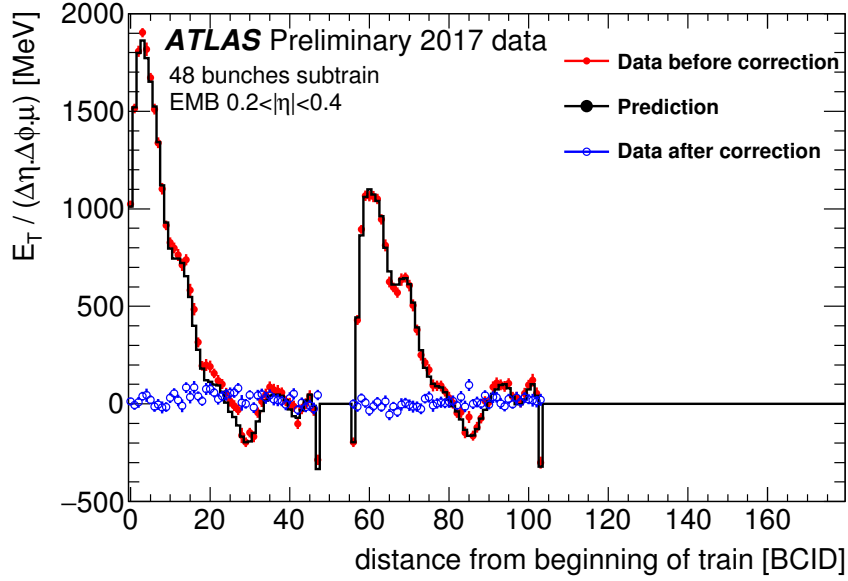


Figure 4. The average transverse energy (E_T) offline per unit $\eta-\phi$ area and unit μ as a function of the distance from the start of the bunch train. The bunch train consists of 2 sub-trains each with a length of 48 bunch crossings and a bunch spacing of 25 ns [8].

trigger signatures. The improvement can be seen in Figure 5, which shows the E_T resolution of HLT topo-clusters with respect to offline topo-clusters in both 2015 and 2016. The figure also highlights the impact of the energy corrections in events at the beginning of each bunch train. The improvement in the energy resolution also led to a reduction of trigger rates, with no loss in trigger efficiencies. The impact was particularly significant for multi-jet and E_T^{miss} triggers.

4. Conclusion

A number of improvements have been made to the ATLAS High-Level Calorimeter Trigger since Run-1. Most notably the reconstruction software has been optimized, allowing for the cell-building and the subsequent topo-clustering to be performed in full-scan mode as the first step in the HLT for jet and E_T^{miss} triggers - thus improving the harmonization between the online and offline reconstruction. And the introduction of cell-level energy corrections for out-of-time pile-up effects at the HLT has improved the energy resolution for all calorimeter-based trigger signatures - leading to a reduction in trigger rates with no loss in trigger efficiencies. These two major developments have resulted in a significant improvement in the performance for Run-2.

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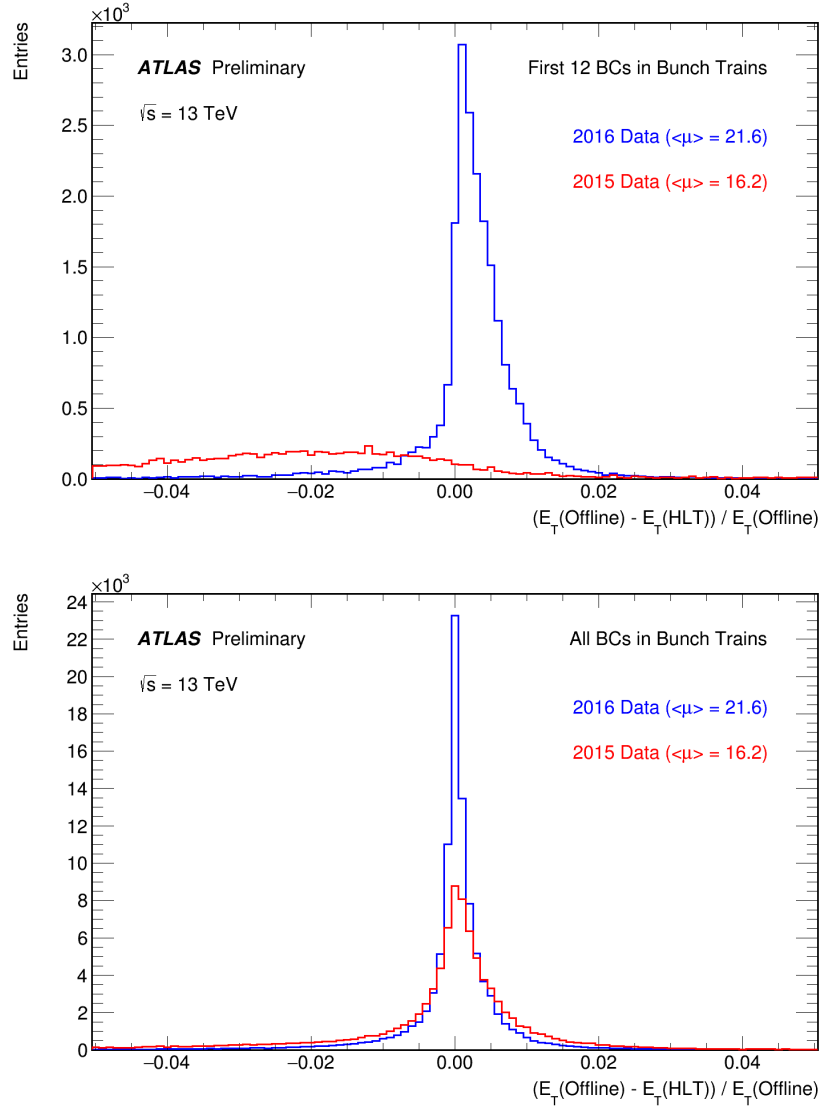


Figure 5. The E_T resolution for HLT topo-clusters with respect to offline topo-clusters with $E_T > 3$ GeV. The data are comprised of bunch trains containing 72 bunches, with a bunch spacing of 25 ns. The bottom shows the E_T resolution for all events, whereas the top shows the E_T resolution for the sub-set of events that correspond to the first 12 bunch crossings in each bunch train [9].

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